Mixed Layer Response to Monsoonal Surface Forcing in the Arabian Sea

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LONG-TERM GOALS

The long-term goal is to observe, understand, and model air-sea interaction, upper ocean variability, and links between the upper ocean and the interior over a wide range of environmental conditions.

SCIENTIFIC OBJECTIVES

An understanding of the dynamics of the upper ocean and of the physical processes that determine its vertical and horizontal structure is sought under the combination of strong surface forcing and energetic oceanic mesoscale variability unique to the Arabian Sea. The combination of strong, sustained monsoonal forcing and eddy variability found there presents the opportunity to study upper ocean dynamics where there is a clearer separation between the time and space scales of the atmospheric forcing and mesoscale ocean variability than in other locations. The response of the Arabian Sea to wind stress and buoyancy flux will be investigated, with the goal of determining the extent to which that response is local and one dimensional, influenced by mesoscale ocean variability or part of a larger scale response to the monsoonal forcing fields.

APPROACH

In the Arabian Sea, in cooperation with T. Dickey, J. Marra, V. Holliday, and C. Langdon, a surface mooring was deployed in the region of maximum wind forcing along the Findlater jet and south of Oman from October 1994 to October 1995. The surface buoy was equipped to collected high quality meteorological data, including wind velocity, air and sea surface temperatures, incoming shortwave and longwave radiation, relative humidity, barometric pressure, and precipitation. Current meters, temperatures recorders, temperature/conductivity recorders, bio-optical instruments, and an acoustics package were deployed on the surface mooring to resolve the vertical structure of the physical and bio-optical fields in the upper ocean. In collaboration with C. Eriksen and D. Rudnick, a 50 km square, four-element array (two profiling current meter (PCM) moorings and two surface moorings with ADCP and temperature recorders) was set around the surface mooring to measure spatial gradients in upper ocean velocity, temperature, and salinity. We deployed current meters and temperature recorders on one of the PCM moorings to extend the observations over the entire depth of the Arabian Sea. Additional data sets (ECMWF, NCEP, satellite, climatological and concurrent ship reports) were obtained to describe the forcing fields.

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The data are being used to test the following hypotheses: 1) Upper ocean response in the Arabian Sea is well-described by one-dimensional physics and biology; 2) Large scale, wind stress curl driven vertical velocities at the base of the mixed layer significantly affect the temporal evolution of the mixed layer; 3) Summer cooling of the mixed layer results from either increased cloud cover, large latent heat loss, lateral advection of cool water upwelled along the Somali and Arabian coasts, upwelling associated with Ekman suction, entrainment at the base of the mixed layer or from a combination of these processes; 4) After the onset of the monsoons, further entrainment at the base of the mixed layer is dominated not by near-inertial shears but by shears associated with sub-inertial wind-driven flow; and 5) Three-dimensional flow associated with mesoscale ocean variability rather than large-scale, wind-stress curl driven flow is the primary source of vertical circulation at the base of the mixed layer. Both one-dimensional and basin-scale, three-dimensional modeling will be done in conjunction with data analysis to address these hypotheses, and the three-dimensional modeling will be a major part of graduate student Albert Fischer's PhD thesis research.

WORK COMPLETED

Final calibrations and corrections to the data from the mooring recovered in October 1995 were completed by late 1996 (Baumgartner *et* al., 1997), and in the past year data has been exchanged with other Arabian Sea investigators. Scientific analyses and publication are in progress. The effort focused first on completing the analysis of the surface meteorological and air-sea flux fields at the moored array and over the Arabian Sea, on developing a description of the observed upper ocean variability, and a preliminary assessment of the ocean dynamics at the moored array.

The work on the surface forcing developed into a collaboration with Peter Taylor and Simon Josey of the Southampton Oceanography Centre (SOC) in the U. K., in which the data from our surface mooring were used to verify the significant improvements Josey and Taylor have made in correcting volunteer observing ship data and in making regional choices for appropriate bulk flux formulae. This work was included in the paper summarizing the analysis of the surface forcing submitted to the *Deep-Sea Research* Arabian Sea volume (Weller *et al.*, 1997). Two other papers on the surface forcing fields were completed as part of Dave Halpern's investigation of differences between satellite remote-sensed winds, numerical weather prediction model winds, and our buoy winds (Halpern *et al*., 1997a, b). The surface meteorology and flux time series from our surface mooring have been made publicly available.

The oceanic variability at our mooring has been examined; two periods of mixed layer deepening and cooling associated with the Northeast and Southwest Monsoons are well documented. A preliminary report on the variability observed from October 1994 to October 1995 by the moored array was published in *EOS* (Rudnick *et al*., 1997). Analyses of both the bio-optical and physical variability observed at our mooring have been reported in Dickey *et al*. (1997), Marra *et al.* (1997), and Wiggert *et al*. (1997).

The dynamics of the two periods of mixed layer deepening, one accompanying the onset of the Northeast Monsoon and the other accompanying the onset of the Southwest Monsoon have been examined. The deepening in the winter of 1994-1995 was driven largely by surface buoyancy flux and the resultant convection in the upper ocean, while that observed in the summer of 1995 was associated primarily with wind-driven mixing. In both cases, though, other effects are apparent. The passage of an eddy influenced the mixed layer depth and eddy-related flow dominated the surface velocity variability during the onset of the Northeast Monsoon. Offshore advection of cool water contributed to the local heat budget during the onset of the Southwest Monsoon. Fischer's Master's Thesis (Fischer, 1997) and a talk at the July 1997 IAPSO (Weller *et al.*, 1997) presented this work.

RESULTS

The buoy returned unique, accurate, year-long time series of surface forcing and upper ocean response in the Arabian Sea. The Northeast Monsoon was found to be characterized by steady but moderate winds, clear skies, relatively dry air, and two months, December and January, in which the ocean lost on average 45 W m^{-2}. The Southwest Monsoon had strong winds, cloudy skies, and moist air and was, contrary to what is shown in some climatologies and numerical model fields, accompanied by sustained oceanic heat gain, with the strongest monthly mean heating of 147 W m^{-2} occurring in August. Comparison of the moored surface meteorological observations and fluxes with the concurrent and climatological data from the SOC climatology shows the 1994-1995 period to be typical.

The maximum mixed layer depths seen in association with the two monsoons were similar, but the dynamics of the deepening and the processes maintaining the upper ocean heat budget were found to be different. During the Northeast Monsoon, convective mixing in response to surface heat loss was more important than wind-driven mixing, near-surface heat budgets were close to one-dimensional, and lateral advection of spatial structure in the thermocline played a role in determining mixed layer depth. During the Southwest Monsoon, wind-driven mixing was dominant and horizontal advection of temperature was important within the mixed layer, as cool water was brought offshore into the moored array. Inclusion of parameterizations of these two horizontal advection effects improved the ability of a local, otherwise one-dimensional, model to simulate the temporal evolution of the sea surface temperature and mixed layer depth.

IMPACT/APPLICATION

The field work produced the first long time series of high quality near-surface meteorology and air-sea fluxes of momentum, heat, and freshwater to be obtained in the Arabian Sea. This will permit critical evaluation of existing climatologies and atmospheric models. Already, comparisons indicate shortcomings in both as sources of information about heat and freshwater fluxes and support the use of the new SOC climatology for further studies of the Arabian Sea. The buoy and SOC data indicate strong heat gain in the summer over the central Arabian Sea, strengthening the case for the dominance of wind-driven mixing and advection as the mixed layer cools. On the basin scale, the better heat fluxes will permit re-examination of basin scale heat budgets and of the meridional circulation inferred from them. The field work also produced the first long time series of upper ocean variability from the Arabian Sea. This will permit quantification of the relative contributions of various processes to the summer cooling and deepening of the mixed layer; a description of mixed layer response to strong, sustained forcing; a description of mixed layer response to strong forcing in a region of strong wind stress curl; and improved understanding of the links between Arabian Sea physical and biogeochemical variability.

TRANSITIONS

Surface meteorological data was telemetered via satellite and after recovery made available to forecast centers. Data from the moored buoys is also being shared with satellite investigators for use in ground-truthing and validating these products.

RELATED PROJECTS

The work described above is being done in collaboration with projects underway by other investigators participating in ONR's Arabian Sea Mixed Layer Dynamics program, including D. Rudnick's (UCSD) and C. Eriksen's (UW) studies of mixed layer dynamics and J Marra (LDEO) and T. Dickey's (UCSB) studies of bio-optical variability. The additional moorings deployed by Rudnick and Eriksen permit estimation of the role of horizontal advection. The mooring data analysis is being carried out in parallel and in collaboration with K. Brink and C. Lee's (WHOI) analysis of SeaSoar data, C. Flagg's analysis of shipboard ADCP data, and J. Kindle's (NRL) modeling work on the surface wind field and upper ocean variability.

Buoy data has been compared with the SOC data (Josey and Taylor, SOC) whose work will lead to basin-wide, improved surface meteorological and flux fields. Buoy data has also been compared with satellite and numerical weather prediction model winds as part of D. Halpern's (JPL) research.

Data and descriptors of upper ocean variability such as time series of mixed layer depth have been shared with JGOFS investigators, particularly with those working on analysis of the moored sediment traps.

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